Visualization on Interactive Surfaces: A Research Overview

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Visualisierung auf interaktiven Oberflächen: Ein Forschungsüberblick

Visualization, interactive displays, survey.

We present a systematic overview of the state-of-the art in research at the intersection between interactive displays and visualization. Because the access to and analysis of information is becoming increasingly important anywhere and at any time, researchers have begun to investigate the role of interactive displays as data analysis platforms. Visualization applications play a crucial role in data analysis and development of dedicated systems and tools for small to large interactive displays to support such application contexts is underway. We contribute a systematic and quantitative assessment of the literature from ten different venues, an open repository of papers, and a code-set that can be used to categorize the research space.

Dieser Artikel enthält eine systematische Übersicht über den aktuellen Stand der Forschung zum Thema Visualisierung und interaktive Oberflächen. Der Zugang zu und die Analyse von Informationen wird in den verschiedensten Situationen zunehmend wichtig. Als Konsequenz haben Wissenschaftler begonnen, die Rolle von interaktiven Bildschirmen für die Datenanalysie zu erforschen und neue Systeme und Werkzeuge für kleine und große interaktive Bildschirme zu entwickeln. Wir tragen eine systematische und quantitative Auseinerandersetzung mit der wachsenden Literatur bei und stellen unsere Datenbasis frei zugänglich online. Darüber hinaus kann unsere Sammlung von Codes dazu benutzt werden, weitere Arbeiten des Forschungsbereichs in der Zukunft zu kategorisieren.

1. Introduction

The careful perusal of diverse and complex information sources is becoming increasingly important in many areas of people's lives: to gain insight, make decisions, and act upon them. For such data analysis tasks, the ability to picture and interact with data has always been a crucial component; not only for higher quality insights and decisions but also for increased confidence and communicability. Vision is our most dominant sense and a large part of our brain is devoted to processing visual information. Visualization and interaction with data are thus essential tools for data analysis—they make data visible, processes understandable, suggest hypotheses for observed phenomena, and aid in making decisions on further actions.

A successful, effective, and efficient visualization tool is, however, not easy to build. An effective mapping from data to visual layout is needed but just as important are effective interactive means for modifying what part of the data is visualized and how. An effective interaction technique needs to allow people to specify their data analysis intent such that the process of intent specification does not hinder the main data analysis task. Mouse and keyboard are the currently assumed standard for specifying a data analysis intent while the desktop monitor serves as the output medium. This assumed data analysis setup, however, is not always the most effective or efficient for example when data has to be analyzed outside of an office environment or with multiple people at the same time. Data analysis contexts outside of a person's individual desk are becoming increasingly common. People carry powerful computers such as smart phones, tablets, or net/notebooks with them, often with the goal to access information anywhere and at any time. They also meet in or generally populate spaces that are increasingly lined and equipped with different kinds of display surfaces. If interaction with visual information displays in these contexts is well supported, these settings can empower humans to more effectively and intuitively attend to and make use of information whenever and wherever it is needed the most. As such, people will begin to demand to access and analyze both personal and work-related information in a variety of contexts and social configurations. The companies or communities that develop data analysis and visualization solutions such as Tableau, Excel, or VTK have already seen this trend and begin to offer ported or adapted versions of their products/systems for smartphones and tablets.

Research has led the way in providing guidelines and design considerations for the development of visualization applications for interactive displays. Researchers have studied how information is best visualized, presented, and interacted with in contexts as diverse as offices, museums, meeting rooms, living rooms, or shopping windows. Since research on interactive displays as well as on visualization has independently seen a huge increase in interest from the public and industry over the last couple of years, it is now time to revisit past work. We need to take a closer look at, in particular, which challenges have been tackled for which types of interactive surfaces as well as for which types of datasets and visualizations. Research on interactive surfaces and on visualization is usually published in dedicated but separate conferences and journals and it is consequently scattered across publishers and digital libraries. It is, thus, not always easy to get a comprehensive overview of the literature. Our goal in this article is to provide a systemic overview of the state-of-the art in interactive display research with a focus on supporting visualization applications. Visualization applications are of particular interest as they offer a unique set of challenges in terms of the technical setup, representational mappings, interaction needs, collaboration, or the evaluation of prototypes—and more research is needed to address them [Isenberg et al., 2013].

We contribute a first assessment of the literature from ten different venues in the area of HCI and visualization. We provide a code set to assess papers at the intersection of visualization and interactive displays and make our literature overview publicly available. The goal of the article is to point out open and under-explored research directions for visualization applications on interactive surfaces and to serve as inspiration and guidance for students, researchers, and practitioners wanting to enter this exciting research direction.

2. Related Work

Only few surveys exist that cover interactive surfaces and we are not aware of any focused at the intersection of interactive surfaces and visualization. Most current overviews have been published as part of thesis research and are usually dedicated to a subset of the space such as collaborative work [Isenberg, 2009] or diagram and graph manipulation [Frisch, 2012]. A book that focuses on research topics related to "under, on, and above interactive tabletops" [Müller-Tomfelde, 2010] provides an overview of the challenges in designing interfaces for this particular type of display; another short overview focuses on large displays only [Czerwinski et al., 2006]. Lee et al. [2012] argued more generally for the adoption of novel interaction modalities for information visualization. In the past, two workshop proceedings were published that also serve as overviews of the types of questions and problems researchers addressed: The Workshop on Collaborative Visualization on Interactive Surfaces (COVIS),[1] held at VisWeek 2009, as well as the Workshop on Data Exploration on Interactive Surfaces (DEXIS),[2] held at the Interactive Tabletops and Surfaces (ITS) conference in 2011. The DEXIS paper by Tominski et al. [2011] identifies several research and practical gaps that have to be addressed before novel displays become commonplace for information visualization. A summary article for the latter workshop [Isenberg et al., 2013] also looks broadly at the types of challenges that research at the intersection of interactive surfaces and visualization entails and draws a first research agenda. Other research agenda articles look specifically at the visualization of spatial 3D data (often called "scientific visualization") [Isenberg, 2011; Keefe and Isenberg, 2013]. In contrast to all of this work, in this article we take a deeper look at the literature in general and analyze the types of displays, data sets, visualizations, and research questions that researchers have addressed in the past. With this work we draw a large amount of literature together in a systematic overview and to more clearly point out open and under-explored research directions.

3. Research Overview: Approach and Code Set

In this article we focus on research at the intersection of interactive displays and the three main visualization research areas (named as such by convention of VIS, the visualization field's largest conference): information visualization, scientific visualization, and visual analytics. In the three areas the layout of data on a (typically) 2D display surface is the crucial problem. Information visualizations typically represent abstract data with no pre-defined layout in 2D space—such as a scatterplot representing multi-dimensional data on a Cartesian coordinate system. Scientific visualizations, in contrast, often have a given underlying spatial layout that is represented in 3D—such as a visualization of the arrangement of stars in a galaxy. Visual analytics deals with both types of visual representations and often also combines them with additional techniques from data mining, machine learning, and other disciplines. Of course, these descriptions are only rough categorizations of the field of visualization in general and the borders of the subfields are fluid. In the research area on interactive surfaces we concentrated on those surfaces that are able to output visual information and receive input within the display environment, either directly on the display or through sensors and actuators integrated into the surface itself.

3.1 Methodology

We took two general approaches to collecting the data for our systematic review. We first identified the conferences that—according to our own experience—published the largest amount of papers on interactive surfaces and visualization. We chose the main conferences in the visualization field (IEEE InfoVis, IEEE VIS—now renamed to SciVis, IEEE VAST, EuroVis, IV). Next we chose the

[1] The CoVis 2009 proceedings were published as a University of Munich technical report, # LMU-MI-2010-2 (download the PDF at http://www.medien.ifi.lmu.de/pubdb/publications/pub/isenberg2010covis/isenberg2010covis.pdf).

[2] The DEXIS 2011 proceedings were published as an INRIA technical report, # 0421 (download the PDF at http://hal.inria.fr/hal-00659469).

	VIS / SciVis	InfoVis	VAST	EuroVis	IV	CHI	ITS / Tabletop	Smart Graphics	CoVis	DEXIS	Other	Sum
Papers	6	9	3	6	4	7	18	6	6	5	8	78
EAs	1	4	1	NA	NA	6	21	NA	NA	NA	NA	33
Sum	7	13	4	6	4	13	39	6	6	5	8	111

Table 1: Coded venues and total number of papers and extended abstracts (EA) at the intersection of visualization with interactive tabletops and surfaces. NA marks those extended abstracts we did not search or that did not exist.

dedicated conference for interactive display research (IEEE Tabletop—later continued as ACM ITS), as well as three other relevant conferences and workshops (SmartGraphics, CoVis 2009, DEXIS 2011). We examined full papers as well as short papers, posters, and demos, if applicable. Posters and demos were pooled as *EA* which stands for "extended abstract." Where available, we started to code in the year 2004 and extracted those submissions that addressed work that relates to both interactive surfaces and visualization. For all but two conferences we looked at every single paper individually. For ACM CHI and the IV conference, we instead used a search-based approach in the ACM and IEEE Xplore libraries as these conferences have well over 100 papers per year and a paper-by-paper assessment was impractical. For this search we combined a keyword search for *visualization* with search terms such as *surface*, *touch*, *pen*, *mobile*, *tablet*, *table*, or *large display*. When we found other highly relevant publications through our search approach we recorded them in an *other* category. In total, we considered a pool of over 1000 publications out of which we extracted 111. Table 1 gives an overview of the coded venues and total number of publications found and assessed. Of course, our survey of the literature is not exhaustive and we may have missed a few papers, in particular if keywords did not include any of our key search terms. Yet, given the broad spectrum of venues we assessed, we are confident that our cross-section of the literature is representative of the state-of-the art in research on visualization for interactive surfaces.

3.2 Development of the Code Set

In the design of any visualization, several important components have to be specified: *data transformations* define what part of the data is to be visualized and pre-process the data to be suitable for visualization; *visual mappings* define the abstract visual form/representation that specify how the data is laid out in space and which visual variables (color, position, ...) encode which part of the data; *presentation mappings* define the style elements (borders, background colors, ...) for a visualization and fully define its final look; *rendering parameters* define how the visualization is finally put on the display medium (screen, projection, or paper); and *interactions* define how one can modify the visualization. These components have been integrated into what is generally called a visualization pipeline (for an overview see [Jansen and Dragicevic, 2013]). In the past, the interaction component of the visualization pipeline has not been specific in terms of the type of interactivity that can be applied to a visualization. One notable exception is the work by Jansen and Dragicevic [2013] who describe interactions as alterations to a visualization pipeline to be able to more specifically study and discuss visualization systems "beyond the desktop." In contrast to their work, we did not analyze past research with respect to individual interactions that affect each step of the pipeline but rather in terms of the physical properties of the interaction with a focus on interactive display technology. An extension in the direction suggested by Jansen and Dragicevic [2013] would be very interesting but difficult as access to the developed system and source code would often be necessary to describe the actual pipelines in detail. For each relevant paper, we coded the following parameters, as much as possible: the nature of the interactive surface (type, size, pixel size), the type of data that was visualized, the type of visualizations that were used, the type of interaction (e. g., touch, pen), the number of simultaneously supported interacting people, and a summary of the research focus.[3] For each category we did a first detailed pass noting most relevant parameters and then condensed codes in one or two subsequent axial coding passes.

3.2.1 Physical Display Properties

Based on their form factors, we grouped interactive surfaces into: *mobile* (such as smart phones or PDAs), *tablet* (modern tablets or surfaces with a similar size, mobility, and sensing), *tabletop* (larger than desktop horizontal displays), *drafting table* (a tilted large surface), *large vertical display* (such as vertically mounted TV-sized touch displays or display walls), and *other* (anything that did not fit the previous categories; a dome screen, for example). While we were generally inclusive in our review (e. g., including tangibles as long as they were used on an interactive surface or to display data), we excluded work where interaction surface and display surface were separate (most drawing tablets, touch/track pads, mouse, etc.) and where the interaction did not occur on a surface or had no immediate relationship to it (e. g., mid-air interaction, glove input, natural language/speech control, etc.). For each type of interactive surface, we also recorded which types of interaction were used on or with the display, excluding off-screen interactions that may have

[3] A summary of this data is available at http://goo.gl/6a0zH .

2D spatial	3D spatial	network	md abstract	text	other	map	3D spatial	graphs	charts	custom	other	mobile	tablet	tabletop	drafting table	vertical display	other	touch	tangible	pen	other	interaction	application	collaboration	software	setup	single	small group
37	24	20	30	6	7	35	23	21	20	8	17	7	26	71	6	21	3	85	14	22	3	60	40	11	5	6	56	54
Data						Visual Representation						Type of Display						Input				Research Focus					Users	

Table 2: Codes used in the review and total code counts. Each paper and EA can include more than one code per category.

also been possible. Interaction modalities we coded were: *touch* (e. g., direct touch on the display), *tangible* (e. g., tracked through markers on the display, or the display itself became a tangible device that could be bent, rotated, or modified otherwise), *pen* (e. g., stylus, markers, or other pens), and *other* (e. g., touch through shadows).

For each paper we also attempted to record the *physical size* and *pixel size* of the display surface used during the implementation and testing of tools and techniques. These measurement serve as references to the types of displays that were in active use in research labs at the time of development but of course many reported solutions can extend to other sizes and resolutions than the ones used during development. We were interested in pixel size and physical size of the surfaces as these properties are important for visualization applications, in particular when it comes to reading and analyzing very large information spaces. Unfortunately, for 48% of all papers we could not determine the pixel size of the used displays and for 45% we did not find the physical size of the display (either because it was not reported or because we could not identify these numbers otherwise).

3.2.2 Visualization Properties

Categorizing data types and visualizations is not a simple endeavor and, consequently, many taxonomies of data types and visualizations exist. We needed a rather broad categorization and opted for a code set based on Shneiderman's [1996] work. For data types we coded *2D spatial* (e. g., geospatial maps or floor plans), *3D spatial* (e. g., medical visualizations of hearts or brains), *text* (e. g., document collections or software code), *networks* (e. g., trees and graphs), *multi-dimensional abstract* data (e. g., tabular data), and *other* (e. g., photo collections or cases where the data type was not clearly discussed or any data type could be used).

These types of data can be visualized in a variety of ways. We, therefore, also recorded the type of visualizations supported by a tool, technique, system, or application. We made a difference between those cases where dedicated visualization techniques were developed for an interactive surface (code: *custom*) and others that just used or slightly modified already established types of data representations. We coded: *maps* (e. g., country maps), *charts* (e. g., bar charts, line charts), *graphs* (e. g., node-link diagrams or tree visualizations), *3D spatial* representations (e. g., volumetric rendering of a human head), and *other* where the visualization type was either not clearly specified or the visualization did not fall in any of the other categories.

3.2.3 Research Focus

With any physical, data, and interaction setup a number of different research questions can be tackled. In the publications we coded, we saw five main research trends emerge:

Interaction techniques: the research is focused on the development—and often comparison—of methods for interacting with data on an interactive surface. These interaction techniques are regularly developed to be generalizable to many different applications, data types, and visualizations. Examples include definition of gesture sets, interaction widgets, or the integration of tangibles with an interactive surface display.

Application: the focus of the work is on developing an application or system that supports a specific domain or set of tasks around an interactive display setup. The focus in on explaining which choices were made when developing the system or application with respect to the requirements of a domain. Such research often includes the design of novel interaction techniques or technical setups but within a specific context and can focus as much on the design of visualizations as on interaction techniques. Examples include: installations in museums, medical tabletop applications, or software visualization systems on tabletops.

Software: the focus of the research is on the development of architectures, libraries, or toolkits for visualization on interactive surfaces. This category also includes work that focuses on writing efficient algorithms that are capable of rendering interactive visualizations.

Collaboration: the focus of the work is on understanding collaboration practices around an interactive display visualization or supporting collaboration through a specific system design.

Technical setup: the research focuses on creating an effective physical interactive surface setup for visualization applications.

4. State-of-the-Art in Interactive Displays for Visualization

In the following discussion of the state-of-the-art we closely follow our general code sets described above. A summary of the results of our analysis can be found in Table 2. In general, we found that the percentage of research on visualization-specific problems in the broader context of interactive display research is still relatively small. For example, the conference on Interactive Tabletops and Surfaces (ITS) which had the highest overall count of papers in our review, published 181 full and short papers in the years 2007–2012. Out of these, 18 were relevant for our review—roughly 10%. For all other conferences (excluding the dedicated workshops), the percentages are much lower. This is not entirely surprising because research at the intersection of two disciplines is difficult and requires expertise on a large number of topics. In this case it ranges from technical specifications of interactive displays all the way to the ins and outs of visual encoding and the visualization pipeline. Nevertheless, we were pleasantly surprised to have found over 100 publications. Next we provide details for the presented research topics and highlight a few examples.

4.1 Data and Visualizations

Most research projects we encountered used 2D spatial (37 publications), multi-dimensional (md) abstract (30×), network (20×), or 3D spatial data (24×). The visual representation of data is typically correlated to the underlying data types. As such it is not surprising that we found a large number of map visualizations (35 publications), graphs (21×), and charts (20×). An inspection of correlation between visualizations and data type did indeed show that md abstract data was typically visualized using charts (20× or 67%), 2D spatial data using maps (31× or 84%), 3D spatial data using 3D renderings (23× or 96%), and network data using graphs (16× or 80%).

Maps were a particularly prevalent type of information representation (in 32% of the publications), perhaps because they benefit particularly well from larger surfaces, have many application areas, and are also relatively well supported by open or freely accessible GIS or mapping systems. In contrast, 3D visualizations of spatial data (in 21% of the publications) are still relatively rare, considering their prevalence in the overall visualization literature. One reason may be the mismatch of interaction space (the 2D touch surface) and the data space (3D) since solving it means coming up with meaningful interaction techniques that translate the 2D input into actions in 3D space [Isenberg, 2011]. Another reason may be—if stereoscopic displays are used—the inherent conflict between stereoscopic viewing in 3D and the location of the input on a 2D plane [Valkov et al., 2011].

Surprisingly, only 8 projects concerned the design of completely new representations of data for the respective interactive displays. An example of a custom-designed visualization for serendipitous discovery is the Bohemian Bookshelf [Thudt et al., 2012]. It includes five novel representations for features of a document collection and was designed for fluid exploration on a drafting table in a library.

4.2 Physical Display Properties

By far the most common type of interactive display used in the reported research projects were tabletop displays (54 publications or 49%), followed by tablets (19× or 17%) and large vertical displays (15× or 14%). The prevalence of tabletop research is perhaps not surprising as they lend themselves well to scenarios that have previously not been subject of much visualization research such as collaborative sensemaking (e. g., [Wallace et al., 2013]), learning (e. g., [Block et al., 2012]), or tangible interaction with data (e. g., [Spindler et al., 2009]). Surprising is the minimal amount of publications on mobile interaction (7 publications or 6%) because smartphones, even though they pose both perceptual and interaction challenges to visualization, offer a multitude of interaction possibilities for data analysis and sharing due to their integrated sensors.

Researchers used 31 different screen sizes and 19 different resolutions. We found displays ranging from 3.7" in the diagonal up to 283". Twelve projects (11%) reported screen sizes of 20" and smaller, 14 (13%) used sizes in the range of desktop monitors (21"–30"), 28 (25%) in the range of large displays (31"–70") and nine (8%) used even larger displays (71"–283"). For 50 papers we could not deduce the physical size of the display. The most common resolution (19x) for this large variety of display sizes was 0.78 Mpx which corresponds to 1024 × 768; followed by 2.07Mpx (11×) which corresponds to 1920 × 1080; Overall, we found resolutions ranging from 0.08Mpx (240 × 320) up to 131 Mpx for a wall display with a 228" diagonal. While the latter wall provides a high ppi count, many other displays we found did not have a high enough ppi for comfortable reading of text. For visualization applications which typically require textual labels to be useful, higher ppi counts are necessary [Müller-Tomfelde, 2010, Chapter 3].

The interactive displays used in the found research prototypes supported predominantly touch input (85×, 76%), followed by pen input (22×, 20%), and tangibles (14×, 13%). The prevalence of touch input is perhaps not surprising as a large number of interactive displays have built-in touch capabilities and no additional hardware needs to be supported. Tangibles were only in use on tabletops, tablets, or mobile displays. In the general HCI literature only very few research projects have explored how tangibles can be used on vertical surfaces without sliding off. Jansen et al. [2012] come closest to addressing this issue in our review. They present tangible sliders for controlling a visualization on a wall display. The sliders can be stuck to a tablet using a suction cup tape and, thus, do not fall off as the tablet is reoriented. Their article also gives a good overview of other interaction modalities for wall-sized displays.

	maps	charts	graphs	3D spatial	other	custom
interaction	16	9	11	15	13	2
application	14	4	11	9	3	5
collaboration	4	5	0	0	1	1
software	2	2	0	0	2	0
setup	4	0	1	1	0	0

Table 3: Research focus for projects that included one or more of the different visualization types.

4.3 Research Focus

The type of research questions addressed by the presented projects is perhaps the most direct indication of open research challenges. We found a large focus on interaction research. This is understandable as with the emergence of interactive surfaces new ways of interacting with data had to be found and evaluated before they could be integrated into dedicated applications. 60 of the 111 publications (54%) included research on interaction techniques. Interaction was the most common research focus for maps (16×), 3D spatial data (15×), other data (13×), and charts (9×). As Table 3 shows, for 3D spatial data 60% of all coded research foci fell into the interaction category, perhaps due to the difficulties of interacting within a virtual 3D environment through a 2D surface as mentioned above. The development of systems and applications was the second most common research focus we found. Maps (14×) were the most common type of visual representation for research applications, followed by graphs (11×), and 3D spatial data (9×). We found a wide variety of applications area, for example: exploration of text document collections, classroom settings, software visualization, reservoir engineering, medical visualization, regional planning, or emergency response. For custom-designed and developed visualizations, applications were the most common research focus. An example of an application-type paper that included custom data visualizations is the Bohemian Bookshelf mentioned above [Thudt et al., 2012]. How to support collaboration was a research focus in 11 projects, including predominantly charts (5×) and maps (4×). In contrast, 54 projects stated that their tool would be usable by small groups, while 56 only supported single users.

The two least common research foci were the development of dedicated technical setups (6×) and software environments (5×). Unfortunately, research on software environments for visualization on interactive surfaces is, thus, still rare. One example is Hugin [Kim et al., 2010], a software framework for developing mixed-presence collaborative information visualization applications.

5. Discussion and Conclusions

In a recent article, Isenberg et al. [2013] proposed a research agenda for visualization on interactive surfaces. This agenda had evolved out of discussions at the DEXIS 2011 workshop and, thus, reflects the experience and past work of all workshop attendees. In contrast, in this article we have taken a different approach and shed light on the types of displays, data, visualizations, and research questions that were the focus of past work. In this discussion we re-visit the proposed research agenda in the light of the quantitative and qualitative overview of research we have gained in our survey.

5.1 Visualization Environments: Technical Challenges

The past research agenda called for dedicated research on the role of different surface types for visualization as well as the use of visualizations in multi-display environments (MDEs). Since different surface types have different affordances they can be more or less suited for certain types of data representations and visualizations. In our review we saw projects for the most common surface types but also less common ones such as a dome screen or a flexible display. Mobile visualizations were very rare, pointing to a still underexplored research area. In addition, few papers compared the role of different surfaces for data analysis or sensemaking. A notable exception is the work by Wallace et al. [2013].

Related is the question of how to use several interactive surfaces in concert. MDEs offer a large discretized display space that can be beneficial to collaborative data analysis or to physically separate semantically different data. Out of all 111 papers we coded, however, only 22 mentioned the use of more than one display type. Thus, MDEs are still a widely open research direction for visualization.

5.2 Visualization Design for Interactive Surfaces

The past research agenda further named dedicated data representations and touch interaction techniques as important areas for further work. As mentioned above, only eight projects focused large parts of their work on the development of custom representations. Even though we saw these few promising examples, the question of how visualizations need to be adapted and redesigned to be effectively perceivable and interactively modifiable is still a largely open research direction.

Despite the large number of publications focused on tackling challenges related to input, more research is needed as the space of possible data manipulations is large. This is further supported by recent work in which a WIMP interface interface that was ported to be touchable was outperformed significantly in comparison to a touch-based data exploration that was based on more direct manipulation [Drucker et al., 2013]. In particular also the problem of how to interact with a higher-dimensional space through a 2D surface is still open. Keefe and Isenberg's [2013] research agenda discusses this issue and the related problem of touch interaction with stereoscopic displays. While stereoscopic viewing is frequently used in traditional visualizations (using CAVEs or the Responsive Workbench, for instance), we still found only very few cases (4×, from 3 unique projects) where people investigated the problems of touch interaction with stereoscopic displays that was mentioned above (for more detail on this problem see the paper by Valkov et al. [2011]). This is unfortunate for two reasons. First, modern technology provides increasingly easy access to both touch input and stereoscopic displays. Second, both touch interaction on surfaces and stereoscopic displays have fundamental advantages over traditional non-touch monoscopic environments. Providing solutions for the use of both features simultaneously would thus be tremendously useful for creating more effective visualization environments for 3D data.

The use of tangibles for data exploration is an upcoming research area that was not specifically covered in our previous research agenda. It was, however, mentioned by Lee et al. [2012] as a promising input modality. How exactly the physical manipulation of virtual data aids in cognition is an open and very interesting research challenge [Lee et al., 2012] that could have impact on a variety of questions in learning, analysis, and knowledge building.

5.3 Social Challenges

The research agendas by Isenberg et al. [2013] and by Keefe and Isenberg [2013] stress the importance of supporting collaborative data analysis as much of today's scientific work is conducted in teams. 48% of the projects we found supported small teams—at least in principle. Unfortunately, only 11 projects actually focused on the support of collaboration. Yet, collaborative work needs dedicated support that goes beyond providing one input per person. For instance, for map applications interaction techniques have to be found that allow more than one person to pan and zoom into the data without disturbing others. For an example solution see Ion et al.'s [2013] work. Interestingly, we found no research projects that specifically focused on how to support collaboration around graphs, 3D spatial, or other data (sometimes being mentioned just as an aside), thus indicating directions for more dedicated research.

5.4 Summary

In conclusion, we found just over 100 publications at the intersection of interactive surfaces and visualization in our careful examination of 10 different publication venues related to the topic. We found that research has so far largely focused on the development of interaction techniques, for multi-touch tabletop devices, and 2D spatial and abstract visualizations. Together, all publications addressed a wide spectrum of research questions and, given the many possible combinations of interactive surfaces and visualization, the research space is still wide open. While several projects developed applications for data analysis with visualization on interactive surfaces, their availability in practice is still rare. Commercial companies and open-source communities have begun to provide ported versions of their products/tools for tablets and mobile phones (e. g., Tableau Mobile[4] and KiwiViewer[5]), showing the need for visualization application on surfaces. Nevertheless, the support for data analysis tasks on these and other interactive surfaces can certainly still be improved—a lot more research with respect to the development and evaluation of the fundamentals of data exploration and analysis is needed for interactive displays. Such work can ultimately also lead to better software support in terms of toolkits and frameworks that would ease the development of visualization applications for interactive surfaces. An ultimate goal should be a catalogue of design considerations for a variety of visualization, interaction, and surface types.

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